BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Sizing of a High Performance Cryogenic Stage for Manned Flyby Missions - Case 233

DATE: July 6, 1967

FROM: H. S. London

ABSTRACT

The effects of stage size and orbit rendezvous mode on payload weight are analyzed for manned planetary flyby missions which utilize a new high performance cryogenic stage for Earth-escape propulsion. It is found that for three-launch missions using standard Saturn V's, payload can be increased approximately 50,000 lb., as compared to previously discussed results (Reference 1) based on a 110,000 lb. stage, through proper selection of stage size and/or rendezvous mode. Maximum performance is attained using three-stage launch vehicles, a cryogenic injection stage of around 200,000 lbs. gross weight, and an elliptical rendezvous orbit.

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MEMORANDUM FOR FILE

INTRODUCTION

Previous Bellcomm studies of a high-performance cryogenic stage for manned planetary flyby missions (References 1 and 2) have concentrated on a H_2/O_2 stage of roughly 110,000 lbs. gross weight, with rendezvous and assembly operations taking place in a two-day period parking orbit. The basis of this selection was that a stage of this size could be placed into the two-day orbit by a single three-stage Saturn V launch vehicle, from where it could then inject a 180,000 lb. spacecraft onto a Mars twilight flyby trajectory. The spacecraft would be placed into the rendezvous orbit in two pieces, making a total of three launches.

The same could be accomplished (i.e., injection of a 180,000 spacecraft onto the Mars flyby, with a total of three launches) using a much larger stage (~ 240,000 lbs. gross weight) and circular orbit rendezvous. In this case two propulsion modules would be required and the spacecraft would be launched into orbit in a single unit. However, the smaller stage size was preferred since it would be better suited for other applications such as a lunar logistics landing stage or as a Saturn V fourth stage for unmanned missions. The smaller stage would also presumably be cheaper to develop.

Neither of these options, however, makes full use of the launch vehicle performance capability. Using the two-day period assembly orbit and the 110,000 lb. injection stage, the 180,000 lb. spacecraft is put into orbit in two pieces, e.g., one of 110,000 lbs. (approximately the maximum capacity of the 3-stage Saturn V to this orbit), and the other of 70,000 lbs. The latter leaves part of the performance capacity of the launch vehicle unused. The second option, of using a larger stage and circular orbit rendezvous, as specified above does not utilize the full capacity of any of the launch vehicles.

Better overall utilization of the launch vehicles, which is to say maximum injection velocity for a given payload or vice-versa, can be obtained by (considering three-launch missions):

[redacted]

1. Allowing a larger propulsion stage, and reverting to two propulsion-stage launches and one spacecraft launch, with the spacecraft placed in the maximum eccentricity orbit of which the launch vehicle is capable, and/or

2. Allowing both the spacecraft and the out-of-orbit propulsion to be divided into two pieces. That is, one launch vehicle carries a propulsion module, one carries the larger piece of the spacecraft, and the third carries both a propulsion module and the smaller piece of the spacecraft. On this last launch the propulsion module uses part of its propellant to transfer itself plus the smaller piece spacecraft from a lower intermediate orbit to the final rendezvous and assembly orbit. This mode is applicable whenever the total spacecraft weight exceeds the propulsion module weight.

ANALYSIS AND RESULTS

The launch vehicle performance was based on the currently quoted capability for SA-516. The two-stage version has a capacity of about 274,000 lbs. to a 100 nautical mile circular orbit; this weight includes everything above the S-II stage. Thus the payload adapter (or aft interstage if the "payload" is a propulsion stage) and IU must be subtracted out to get actual payload. To be conservative, this was assumed to total 12,000 lbs. in all cases (approximately the weight of the S-IVB aft interstage plus the current IU) so that net payload to a 100 nautical mile orbit is 262,000 lbs. The ΔV available, above that required for a 100 nautical mile circular orbit, for smaller payloads was calculated from the ideal ΔV equation assuming no change in gravity losses. The three-stage version was assumed to have a capability of 100,000 lbs. to trans-lunar injection and 264,000 lbs. in a 100 nautical mile orbit; these payloads are everything above the IU. The complete payload velocity curves are shown in Figure 1.

The payload which can be injected from the rendezvous orbit was calculated as a function of the injected velocity of the payload, expressed as total ΔV above a 100 nautical mile circular orbit. In all cases, the injection propulsion modules were assumed to have a specific impulse of 460 sec. and mass fraction of 0.9. Results are presented only for the case of three-launch missions.

MODE 1

The first mode considered simply uses two propulsion modules, each put into orbit with a single launch, and one spacecraft launch. The spacecraft is placed into the most eccentric orbit (with periapse altitude specified as 100 nautical miles) which is possible for that weight with the Saturn V launch vehicle. If the propulsion module weight is greater than the spacecraft weight, the propulsion modules are also placed into the most eccentric possible orbits (lower than the spacecraft orbit). A first burn is then used to transfer each propulsion module up to the spacecraft's orbit where rendezvous and assembly take place. If on the other hand the spacecraft is heavier than the propulsion module, then the propulsion modules are brought up to the spacecraft's orbit by the launch vehicle directly. In either case, the propulsion modules are assumed to be docked with the spacecraft and ignited in series to provide the earth departure injection ΔV.

The injection velocity was calculated as a function of payload weight, for either two-stage or three-stage launch vehicles. In both cases, the variation of injection velocity with propulsion module gross weight was also determined for various spacecraft weights. The following results were obtained:

a. Three-stage launch vehicles - The optimum propulsion module weight is always equal to or greater than the spacecraft weight. However for a fixed spacecraft weight the curves of injected velocity vs. propulsion module weight are quite flat as shown in Figure 2, so that it is possible to pick a propulsion module weight which gives near-maximum performance over a range of spacecraft weights. A good value appears to be about 200,000 lbs., since this gives near optimum performance for spacecraft weights of 200,000 lbs. or less, although it falls off sharply for spacecraft weights greater than 200,000 lbs. This sharp falloff in performance for a fixed propulsion module weight always occurs when the spacecraft weight exceeds propulsion module weight, regardless of what the propulsion module weight is. The reason for this is that although the launch vehicle performance would allow placing the propulsion module in a higher orbit than the spacecraft, it would not be possible to rendezvous without first applying a retro ΔV to the propulsion module, which would be wasteful; therefore, the propulsion module is placed directly into the same orbit as the spacecraft, and therefore, the launch vehicle performance is not fully utilized.

This effect is illustrated in Figure 3 by curves A and B which are for 200,000 lbs. and 180,000 lbs. stages respectively. For payloads less than 180,000 lb. the two curves are essentially identical; curve B slopes off rapidly for payloads greater than 180,000 lbs. and curve A for greater than 200,000 lbs.

Thus something like 200,000 lbs. appears a reasonable choice for stage size in this operational mode since it allows near-optimum performance for spacecraft weights up to 200,000 lbs. Larger stages give better performance only if the spacecraft weight is greater than 200,000 lbs.

b. Two-Stage Launch Vehicles - The launch vehicle modifications required to permit carrying stages or spacecraft greater than about 135,000 lbs. on top of an S-IVB have not yet been studied. Therefore, the injection performance under the constraint of two-stage launch vehicles has also been investigated.

In this case, it appears that performance is optimized with a stage of S-IVB size or somewhat greater and using suborbital start. However, only a very small net performance penalty is indicated if the stage size is selected as the 100 nautical mile circular orbit capability of the two-stage Saturn V (262,000 lbs.); furthermore, these calculations did not account for increased Saturn V gravity losses as the stage weight increases, which would decrease slightly the actual optimum stage size. Placing the injection propulsion module into a circular orbit initially rather than using a suborbital start also simplifies operations somewhat since one less engine start of the module is required. The injected payload capability vs. injection velocity, using 262,000 lb. stages plus two-stage Saturn V's, is shown as curve C in Figure 3. In this case, the stages are first put into a low circular orbit and then burn up to the elliptic rendezvous orbit where they are joined with the spacecraft.

Since in this case near-optimum performance is obtained with the spacecraft placed in elliptic orbit but the propulsion modules initially in a circular orbit, the penalty for carrying out the rendezvous and assembly operations in the low circular orbit altogether was assessed. This is shown by curve D in Figure 3. For large payloads, the penalty is quite small, but increases somewhat with decreasing payload (or increasing injection velocity), e.g., a payload difference of about 11,000 lbs. at the velocity for a triple-planet flyby mission.

Two important conclusions can be drawn from the curves of Figure 3: First, that in the range of velocities including Mars twilight flybys and the multi-planet missions of interest (~ 15,000 - 17,000 fps), the two-stage launch vehicles with S-IVB size out-of-orbit injection stages provide essentially the same performance as three-stage launch vehicles plus a somewhat smaller injection stage. Furthermore, if the two-stage launch vehicle configuration with the large new cryogenic injection stage is selected, then the penalty for dropping back to the circular orbit rendezvous mode is relatively small, 10,000 lbs. or less in payload. Secondly, any of these options in Mode 1 provides a large payload increase--between 40,000 and 70,000 lbs.--as compared with the baseline mode (one 110,000 lb. injection stage, spacecraft launched in two pieces) which is indicated by the dotted curve in Figure 3.

MODE II

The reason that the baseline mode is relatively inefficient is that one of the launches only carries a partial load--the smaller piece of the spacecraft. This can be remedied by carrying a two-piece out-of-orbit propulsion system as well as a two-piece spacecraft, such that the full capacity of all three launch vehicles is utilized. One way of doing this would be to carry a small propulsion stage on the same launch as the smaller part of the spacecraft, e.g., for a gross spacecraft weight of 180,000 lbs., one launch vehicle would carry a 110,000 lb. propulsion module, one would carry a 110,000 lb. piece of the spacecraft, and the third would carry a 70,000 lb. spacecraft package plus a 40,000 lb. propulsion module. However, developing two different propulsion modules for flyby missions has obvious drawbacks.

An alternative is to carry two identical propulsion modules, one launched by itself and the other combined with the smaller spacecraft package. The latter combination is too heavy to be launched directly into the elliptic rendezvous orbit where the other propulsion module and spacecraft package will be; it is first placed in an intermediate orbit. The propulsion module is ignited to transfer itself with part of its propellant remaining plus the small spacecraft package to the final orbit. The remaining propellant in this propulsion module plus the full capacity of the other is then available for the earth departure injection burn.

More complicated docking and injection operations are inherent in this mode. One possible sequence is to dock the two spacecraft pieces together, with the propulsion modules at opposite ends (and pointing in opposite directions). The partially depleted one is fired first during the injection maneuver and then jettisoned. The whole spacecraft must then be turned 180° before the full propulsion module is ignited.

The sequence of events in this mode is illustrated in Figure 4.

The Mode II is applicable of course only if the propulsion module weight is less than the total spacecraft weight. Otherwise, it simply reduces to Mode 1.

This mode significantly increases the injection performance of the 110,000 lb. stage as compared with the baseline mode; e.g., for a Mars twilight flyby the payload is increased about 40,000 lbs. as shown in Figure 5. Thus, with Mode II the 110,000 lb. stage is competitive with larger stages using Mode 1. However, the performance of larger stages can also be significantly improved with Mode II rendezvous when gross spacecraft weight exceeds propulsion module weight. Figure 5 includes payload-velocity curves for several different propulsion module weights (W_{PM}) using Mode II whenever $W_L > W_{PM}$ to avoid the performance dropoff with Mode 1 (Figure 3). A propulsion module gross weight of about 200,000 lbs. now seems to be near optimum over the entire range of injection velocities regardless of spacecraft weight. The injection payload is 10,000 - 20,000 lbs. greater than with 110,000 lb. modules plus Mode II, and is anywhere from 40,000 to 70,000 lbs. greater than the baseline mode. Note that scaling effects of the stage size have not been included in this analysis; i.e., it is to be expected that the propellant fraction, λ, will be somewhat better for larger stages, whereas a fixed λ of 0.9 was assumed for all stages.

CONCLUSIONS

The following are deduced from the results given above, for three-launch missions and assuming a new cryogenic stage with I_{sp} = 460 sec. and λ = 0.9:

1. Maximum performance is attained with three-stage launch vehicles plus injection stages of about 200,000 lbs. gross weight, using the Mode II rendezvous previously described if spacecraft weight is greater than 200,000 lbs.

2. Comparable although slightly lower performance can be attained with two-stage Saturn V's and a larger injection stage--essentially an S-IVB replacement. The payload decrement for a given velocity is generally around 10,000 - 15,000 lbs. still using elliptic orbit rendezvous.

3. If two-stage Saturn V's plus the large injection stage are used, circular rather than elliptic orbit rendezvous can be utilized with a relatively small additional payload degradation--about 10,000 lbs. or less for flyby missions.

4. If for other reasons small injection stages (on the order of 110,000 lbs. gross weight) are preferred, flyby mission payload can be increased about 40,000 lbs. by using Mode II rendezvous, as compared to the baseline mode of one 110,000 lb. injection stage launch and two spacecraft launches. In this way the small stage can be made competitive with, although still 10,000 - 20,000 lbs. below, the injected payload capability of larger stages.

H S London

1013-HSL-pdm H. S. London

Attachments:
References 1 and 2
Figures 1-5

REFERENCES

1. "Other Mission Applications for a Cryogenic Injection Module," Bellcomm Memorandum for File, dated November 23, 1966 by H. S. London.

2. "Preliminary Design of a Cryogenic Planetary Propulsion Module," Bellcomm TM-67-1013-2, dated May 10, 1967 by M. H. Skeer.

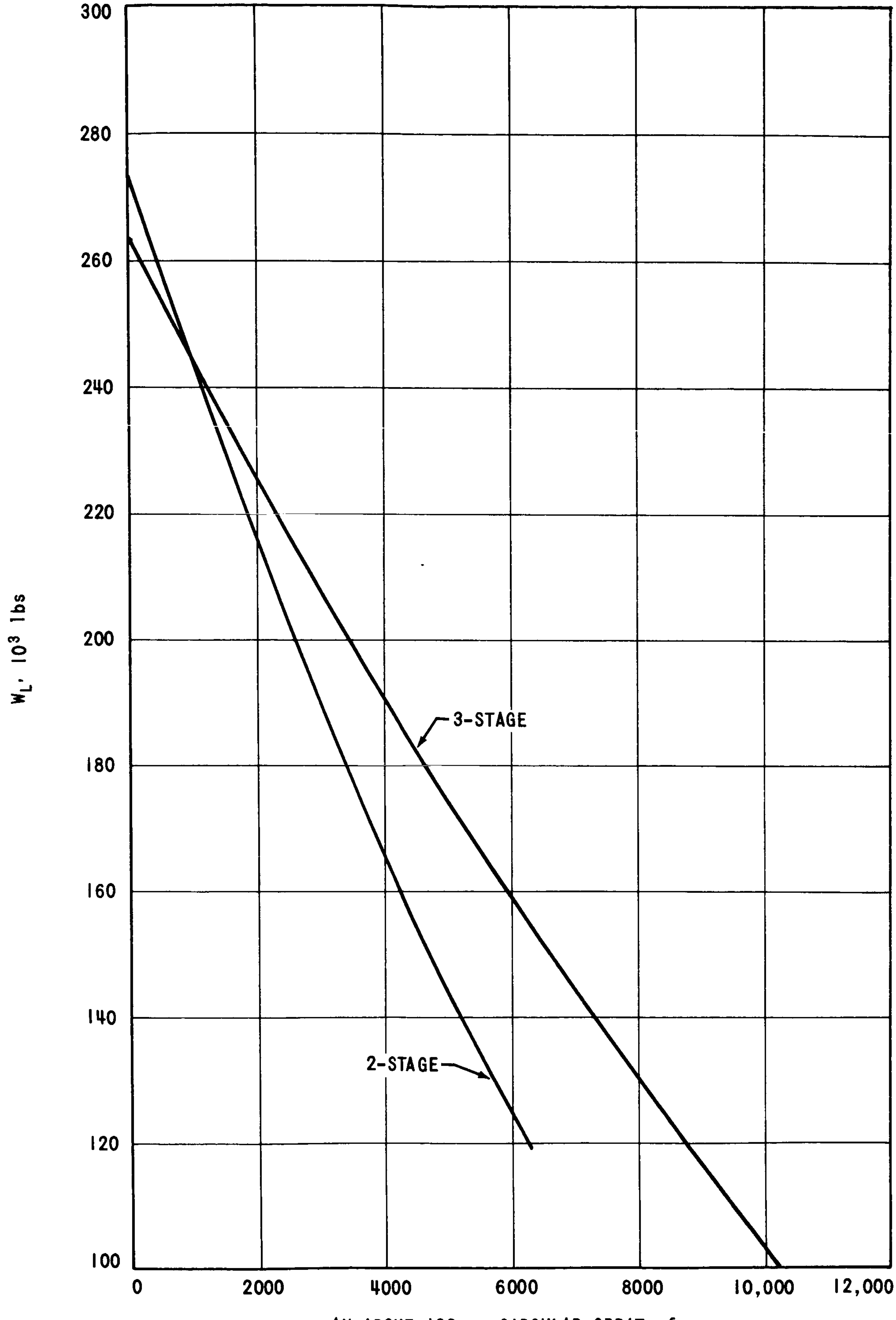

FIGURE I PAYLOAD vs VELOCITY
STANDARD SATURN V

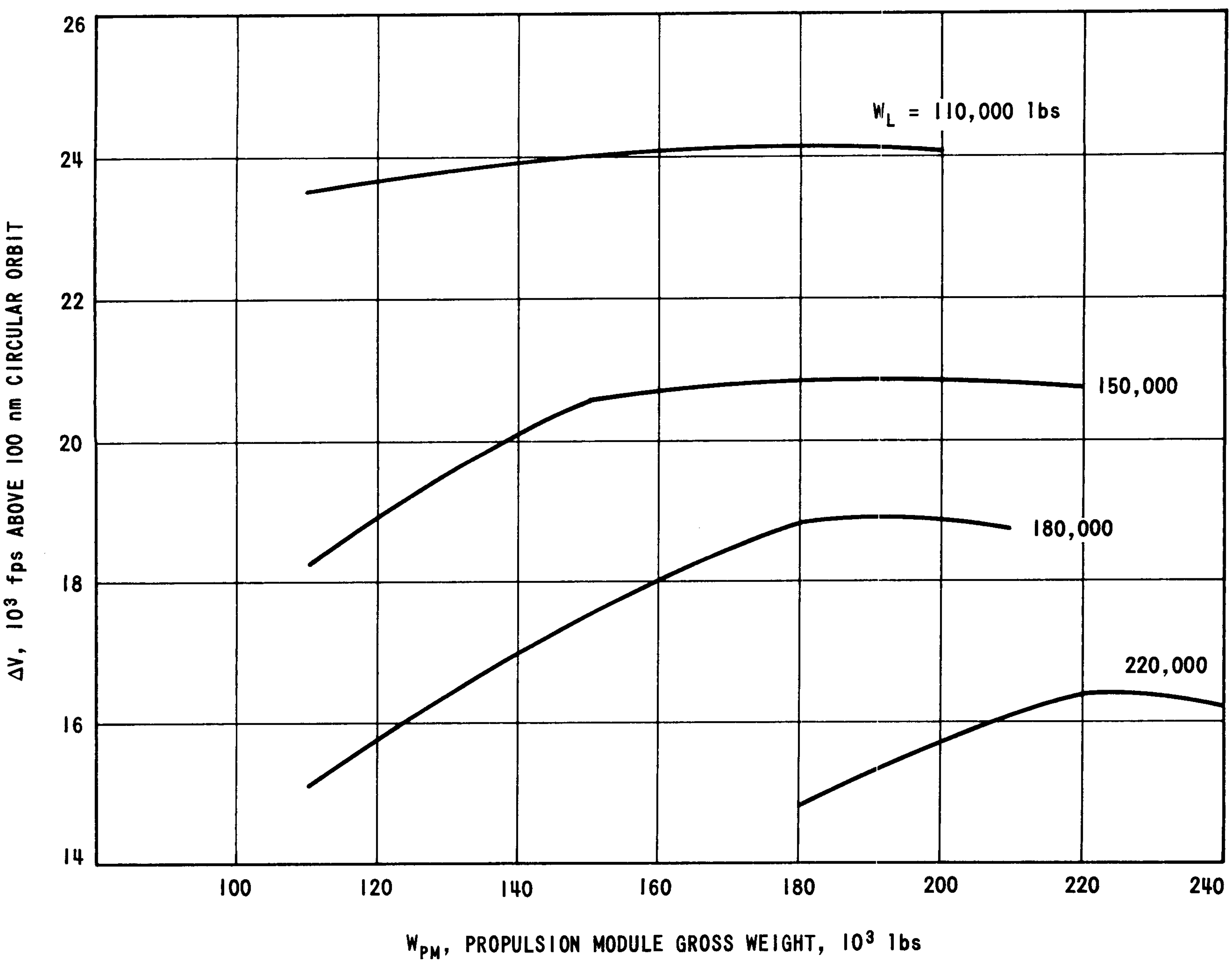

FIGURE 2 MODE I - EFFECT OF PROPULSION MODULE WEIGHT

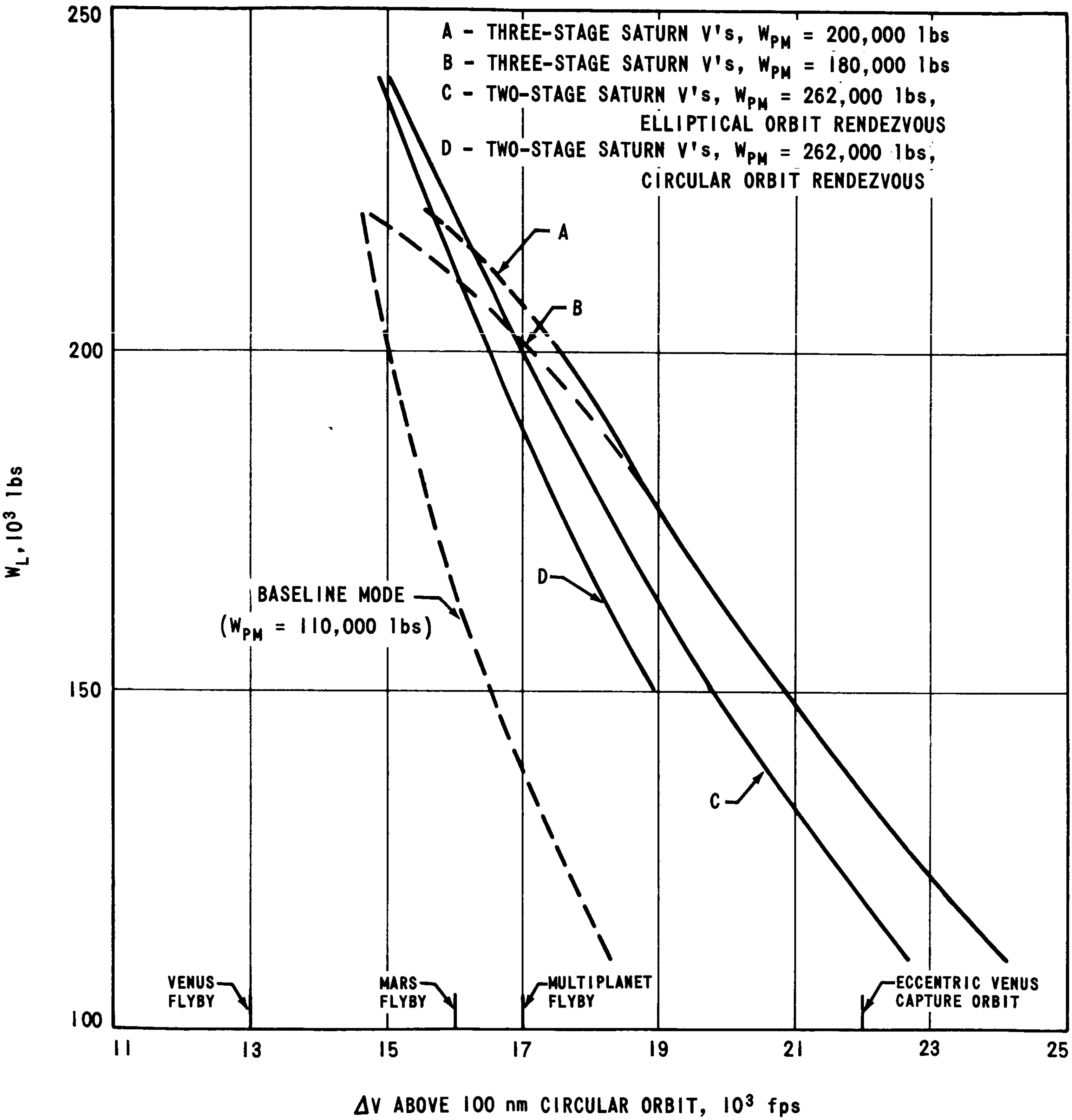

FIGURE 3 PAYLOAD vs VELOCITY
THREE LAUNCHES, SATURN V's

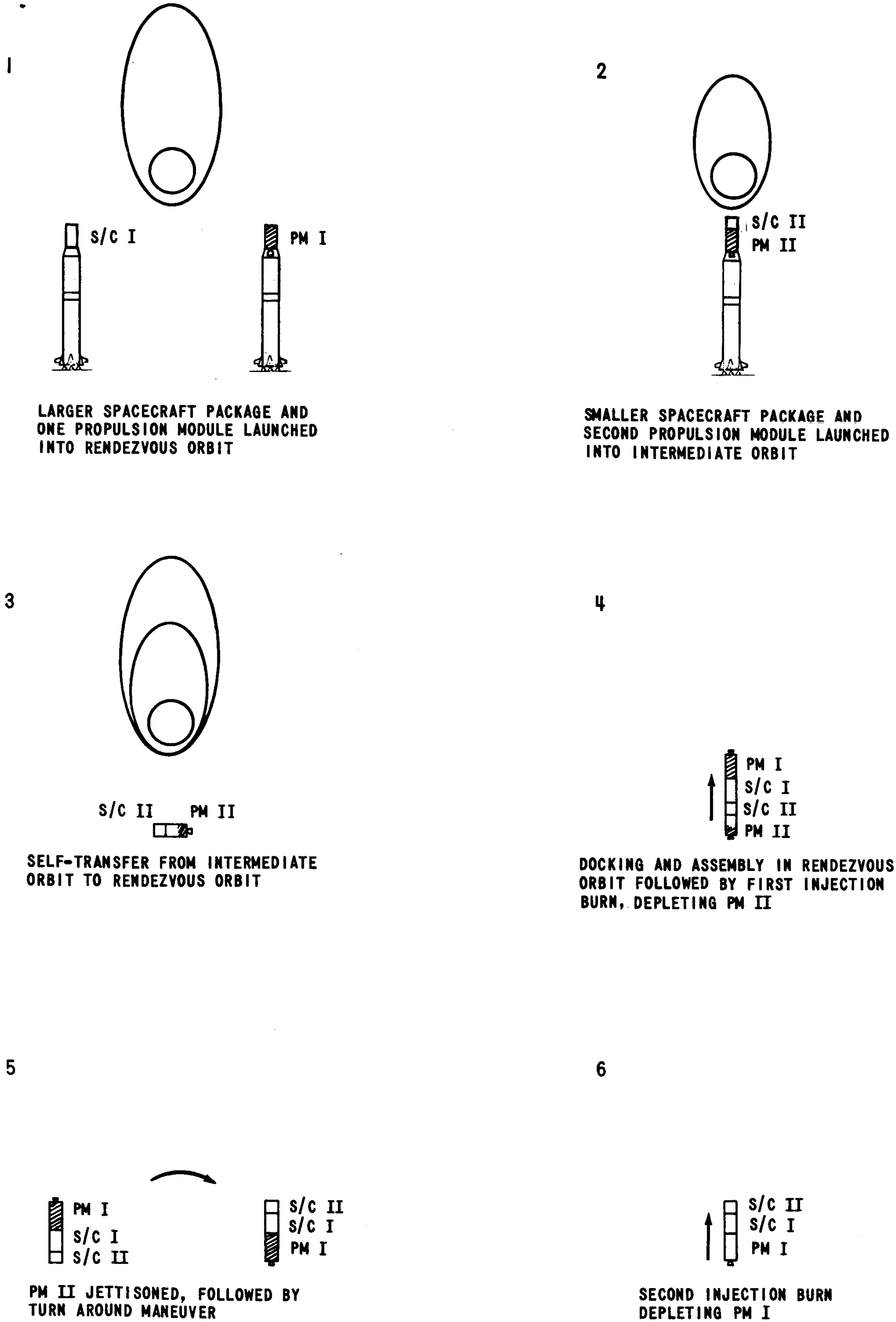
1
S/C I
PM I
LARGER SPACECRAFT PACKAGE AND ONE PROPULSION MODULE LAUNCHED INTO RENDEZVOUS ORBIT
2
S/C II
PM II
SMALLER SPACECRAFT PACKAGE AND SECOND PROPULSION MODULE LAUNCHED INTO INTERMEDIATE ORBIT
3
S/C II
PM II
SELF-TRANSFER FROM INTERMEDIATE ORBIT TO RENDEZVOUS ORBIT
4
PM I
S/C I
S/C II
PM II
DOCKING AND ASSEMBLY IN RENDEZVOUS ORBIT FOLLOWED BY FIRST INJECTION BURN, DEPLETING PM II
5
PM I
S/C I
S/C II
S/C II
S/C I
PM I
PM II JETTISONED, FOLLOWED BY TURN AROUND MANEUVER
6
S/C II
S/C I
PM I
SECOND INJECTION BURN DEPLETING PM I

FIGURE 4

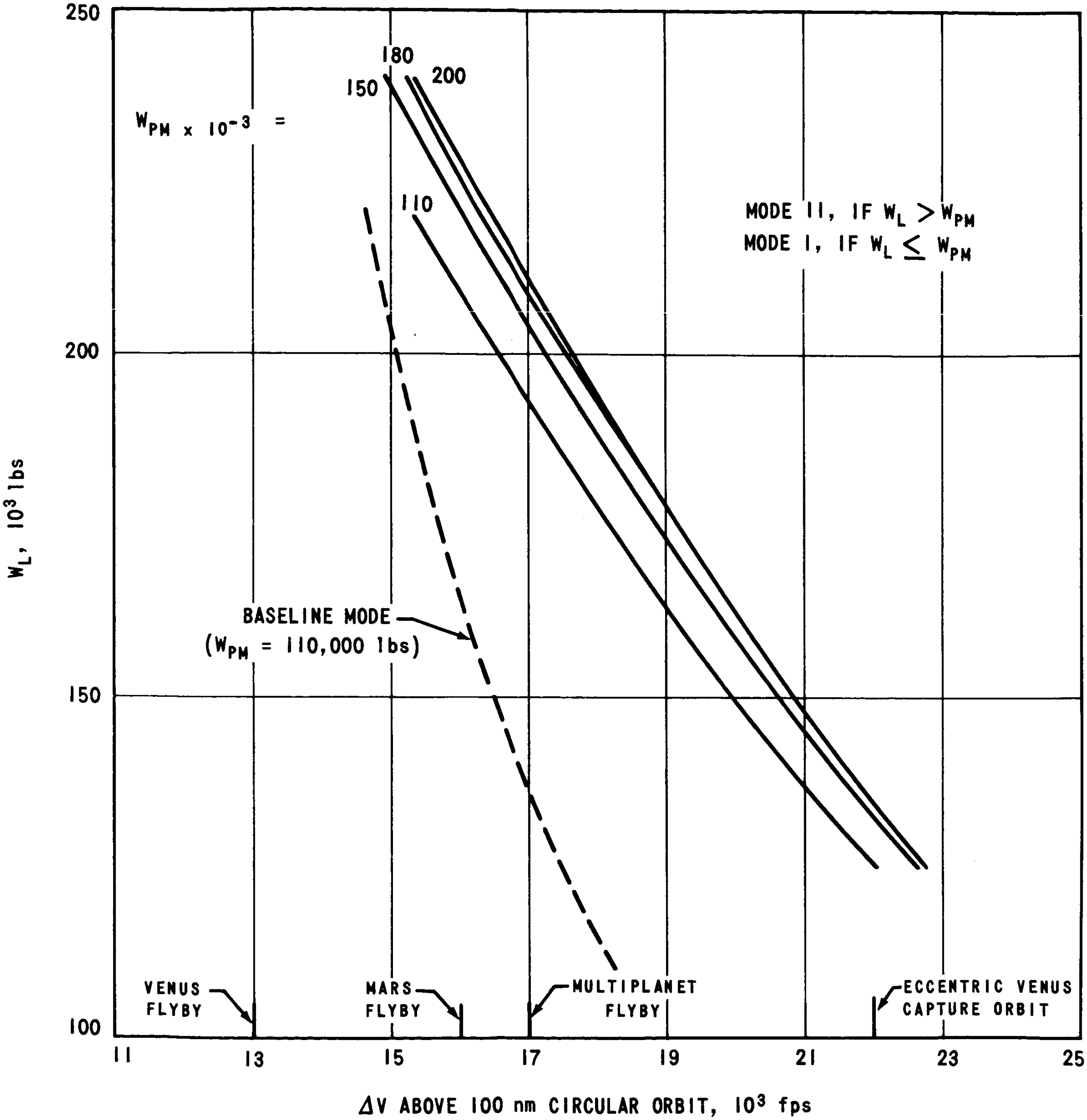

FIGURE 5 PAYLOAD vs VELOCITY
THREE LAUNCHES, THREE STAGE SATURN V's

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